# DAMAGE CLASSIFICATION IN REINFORCED CONCRETE BEAM BY ACOUSTIC EMISSION SIGNAL ANALYSIS

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**2014**

**DAMAGE CLASSIFICATION IN REINFORCED CONCRETE BEAM BY ACOUSTIC EMISSION SIGNAL ANALYSIS**

**by**

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**Thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy (PhD)**

**February 2014**

## ACKNOWLEDGEMENTS

Alhamdulillah, all praises to Allah SWT, the Al-Mighty, for blessing me with strength and motivation to complete my PhD Research towards the end. I would like to thank my parents (Dah Osman and Abd Rahim Jusoh), my parents in-law (M.Zuki and Kalsum) and my grandmothers (Samsiah Man and Timah Darus) for their external support, love and encouragement throughout my studies. They have made me more confident to face the obstacles especially during the project progression.

Special thanks and deepest appreciation to my supervisor Dr Norazura Muhamad Bunnori. She was very supportive and willingly shared her time and knowledge on real practices in Acoustic Emission (Structural Health Monitoring) with me without any hesitation. I would like to thank my co-supervisor ( Assoc. Prof. Dr. Megat Azmi Megat Johari, Assoc. Prof. Dr Mahmod Othman from Uitm, and Dr Neeraj Bharwaj) for giving me adequate freedom and flexibility time while working on this project. I have greatly benefited from a number of useful discussions with all of them, particularly with regard to the research and current issues. Also special thanks to Cardiff University especially to Prof Karen Holford, Rhys Pullin and Shukri Muhamad during attachment program for sharing their knowledge on Acoustic Emission analysis.

I would like to extend my heartfelt appreciation to Ministry of Higher Education (MOHE) and UTHM for providing me Scholarship (SLAB) to assist my studies financially. I would to further my special thanks to all administrative staff and technicians (Mr Shahril, Mr Abdullah, Mr Fadhil and Mr Fauzi) from School of Civil Engineering, USM for their assistance while I was conducting my test in the lab.

I would also like to express my gratitude to my lovely sibling (Shahily's family, Norita's family, Rizan's family, Razak's family, and Nurashikin), my special aunty (Hasnah, Haliza, Marzita, Rusni, Musriah, Noriah, Jam, Ninie, Norma, Kamariah) and uncle (Akhiar, Abd Jamil, Hashim, Hamzah, Aziz, Abu Bakar, Osman, Kassim)  also my close cousin (Ayuni's family, Awani, Amiri, Afifi, Amirul's family, Amin's family, Yantie's family, Fazli's family, Nurhidayah's family) for giving me moral support to complete my PhD studies and also special Timah Abu's Family and Abdul Rahman's Family. Thank you very much.

Finally, I would like to take this opportunity to convey my gratitude and appreciation to my research group (Idanur, Alireza, Majed, Nazlee, Sakhiah, Ramziah) for their knowledge sharing and guidance. Also not forget to my lovely wife (S. Salwa) and lovely friends (Azizi, Naz, Razealy, Am, Ijam, Nuar, Zif, Kim, Fiz, Fuad, Fahmi, Fizi, Rushdi, and Boy's Group) and other colleagues for their guidance and assistance they have given to me. Thank you very much.

Last but not least, this thesis would also be dedicated to my late father (Shahidan Saad) and grandfather (Osman Mahmud & Saad Abu) whose are my inspiration to complete my PhD thesis.

**Shahiron Shahidan**

**February, 2014**

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## TABLE OF CONTENTS

## LIST OF FIGURES

# LIST OF TABLES

# LIST OF SYMBOLS

| | | |
|---|---|---|
| $\Delta_r$ | - | Residual Deflection |
| $\Delta_{max}$ | - | Maximum Deflection |
| $P_{min}$ | - | Loading Minimum |
| $P_{max}$ | - | Loading Maximum |
| $P_{ref}$ | - | Loading Reference Point |
| $V$ | - | Voltage of electrical signal |
| $\alpha$ | - | Angle Load deflection |

## LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| **ABSE** | - | Absolute Energy |
| **AE** | - | Acoustic Emission |
| **AESUM** | - | Acoustic Emission System User Manual |
| **Amp** | - | Amplitude |
| **AFREQ** | - | Average Frequency |
| **ASTM** | - | American Society of Testing Material |
| **ASNT** | - | American Society of NDT Testing |
| **AST** | - | Auto Sensor Test |
| **CLT** | - | Cyclic Load Test |
| **CSS** | - | Cumulative Signal Strength |
| **CABSE** | - | Cumulative Absolute Energy |
| **HDT** | - | Hit Definition Time |
| **HLT** | - | Hit Lockout Time |
| **IA** | - | Intensity Analysis |
| **IEA** | - | Intensity Energy Analysis |
| **ISA** | - | Intensity Signal Analysis |
| **LS** | - | Loading Set |
| **NDT** | - | Non-Destructive Testing |
| **PA** | - | Parameter Analysis |
| **PAC** | - | Physical Acoustic Corporation |
| **PDT** | - | Peak Definition Time |
| **RC** | - | Reinforced Concrete Structure |
| **RT** | - | Rise time |
| **SAMOS** | - | Sensor based Acoustic Multi Channel Operation System |
| **SHM** | - | Structural Health Monitoring |
| **TOA** | - | Time Of Arrival |

**PENGKELASAN KEROSAKAN DALAM RASUK KONKRIT TETULANG OLEH AKUSTIK EMISI ANALISIS**

## ABSTRAK

Pemantauan kesihatan struktur (SHM) merujuk kepada proses pelaksanaan mengesan kerosakan di peringkat awal dan pencirian struktur kejuruteraan. Penemuan kerosakan di peringkat awal dan pemulihan yang sepatutnya akan membantu mencegah kegagalan struktur, menjimat kos senggara di samping memastikan keselamatan struktur dalam jangka hayat perkhidmatan. Pada hari ini SHM digunakan secara meluas terutama dalam sistem pengawasan berterusan masa nyata dengan penglibatan tenaga kerja yang minima. Salah satu kaedah yang paling baik dalam SHM untuk sistem pengawasan berterusan masa nyata adalah akustik emisi (AE). Gelombang AE adalah gelombang tekanan frekuensi tinggi yang dikeluarkan oleh pelepasan pantas tenaga dari sumber bahan setempat contohnya permulaan rekahan dan pertumbuhannya. Teknik AE melibatkan proses merekod gelombang tersebut melalui pengesan yang dilekatkan di permukaan dan kemudiannya menganalisa isyarat untuk mendapatkan maklumat mengenai sifat semulajadi sumber tersebut. Sensitiviti tinggi terhadap pertumbuhan rekahan, keupayaan untuk kenalpasti lokasi, sifat pasif dan kemungkinan menjalankan pengawasan secara masa nyata adalah beberapa ciri-ciri menarik teknik SHM. Di sebalik semua kebaikan ini, masih terdapat cabaran dalam menggunakan teknik AE untuk aplikasi pemantauan, terutama dalam menganalisa data AE yang direkod kerana data selalunya dihasilkan secara banyak sewaktu pengawasan tersebut. Perlunya analisa data yang berkesan dalam sistem penggredan boleh dikaitkan kepada tiga tujuan utama pemantauan; (a) untuk membangunkan sistem penggredan (b) mengenalpasti dan bezakan parameter data AE (c) mewujudkan satu sistem penggredan baru untuk penilaian tahap keterukan. Dalam kajian ini, kaedah ujian beban kitaran (CLT)

adalah cara pertama untuk sistem penilaian. Kaedah ini adalah baru berbanding yang lain, dan boleh memberi wawasan baik kepada status integriti struktur di samping bergabung dengan sistem penilaian AE. Dalam penilaian data parameter AE, kaedah konvensional dikenali sebagai analisa parameter (PA) digunakan untuk menilai struktur konkrit tetulang (KT). Kajian ini telah mengesyorkan dan menguji parameter tenaga mutlak dalam proses penilaian untuk menentukan tahap kerosakan struktur konkrit tetulang (RC). Tambahan lagi, corak rekahan dalam rasuk konkrit tetulang (KT) telah dikenalpasti mengikut jenis proses rekahan dan klasifikasi rekahan menggunakan parameter data AE, terutamanya amplitud AE, masa naik dan purata kekerapan. Semua parameter data ini telah dianalisa menggunakan kaedah statistik nilai-b dan analisa nilai RA. Alat penaksiran untuk menilai tahap keterukan kerosakan telah dijelaskan secara terperinci dalam aplikasi penggunaan. Walaupun beberapa kaedah penaksiran kerosakan dicadangkan dalam teknik AE, tidak semua memperolehi persetujuan sejagat atau sesuai untuk semua situasi. Kaedah-kaedah IEA dan ISA yang melibatkan parameter mutlak tenaga dan kekuatan isyarat diselidiki untuk menentukan tahap kerosakan dalam struktur konkrit tetulang (KT). Cara ini didapati memberi keputusan memberangsangkan dalam analisa parameter data AE untuk menentukan sistem penggredan kerosakan. Dengan melibatkan isu utama ini, dipercayai tesis ini telah membantu menambahbaik keberkesanan teknik AE untuk SHM di bidang kejuruteraan awam.

# DAMAGE CLASSIFICATION IN REINFORCED CONCRETE BEAM BY ACOUSTIC EMISSION SIGNAL ANALYSIS

## ABSTRACT

Structural health monitoring (SHM) is known as assessment on damage detection in structural engineering. Nowadays, the application of SHM has been widely used especially on the continuous real time monitoring system with minimum labour involvement. One of the most excellent tools in SHM for real time monitoring system is Acoustic emission (AE). AE waves are high frequency stress wave generated by rapid release of energy from localised sources with a material, such as crack initiation and growth. High sensitivity to crack growth, the ability to locate source, passive nature and the possibility to perform real time monitoring are some of the attractive features of AE technique. In spite of these advantages, challenges still exist in using AE technique for monitoring applications especially in analysing recorded AE data as large volume of data are usually generated during monitoring. The need for effective data analysis in grading system can be linked into the three main objective of this research; (a) determine the grading system; (b) identify and discriminate the AE data parameter ; (c) and validate a new standard grading system for severity assessment. In this research, cyclic load test (CLT) method is the first method used for this evaluation system. This is a relatively new method that may provide a good insight into structural integrity status and also collaborates with the AE evaluation system. In the evaluation of AE data parameters, the conventional method known as parameter analysis (PA) was used to evaluate the reinforced concrete (RC) structure. This study has proposed and tested the absolute energy parameter in the evaluation for determining the damage level in RC structure. In addition, the cracks patterns in RC beam have been identified according to the type

of cracking process and the cracks classifications by using the AE data parameters mainly AE amplitude, rise time, and average frequency. These data parameters have been analysed by using the statistical methods of b-value and RA value analysis. Quantification tool to assess the severity of the damage is extensively described in the practice applications. Even though different damage quantification methods have been proposed in AE technique, not all achieved universal approval or suitable for all situations. The IEA and ISA methods that involved the absolute energy and signal strength parameter were investigated for determining the damage level in RC structure. This was found to provide encouraging result for the analysis of AE data parameters in determining the damage grading system. By addressing this primary issue, it is believed that this thesis has helped to improve the effectiveness of AE technique for SHM in civil engineering.

# CHAPTER 1: INTRODUCTION

## 1.1 Background of Study

Structural health monitoring (SHM) refers to the process of implementation on early damage detection and characterization for engineering structure. Basically early detection of damage and appropriate rehabilitating will aid in preventing the structural failure, save cost spend on maintenance and ensuring the structural safety for service life. Nowadays, SHM has been widely used especially on the continuous real time monitoring system with minimum labour involvement. Therefore, SHM has been given a significant attention and widely accepted in all engineering systems such as aerospace, mechanical and civil engineering. This system has been applied for long time ago for assessing the damage detection in structure and mostly applied to aerospace and mechanical engineering (Holford et al., 2008).

In civil engineering, SHM is very applicable for evaluating the condition and performance of the structural system especially for high loading structure conditions. The typical applications of SHM systems were carried out on high rise buildings, bridges, dams, river navigational facilities and etc. All these structures involve the public and require extensive safety measure on the structure maintenances. However, it is important to avoid any unexpected failure for ensuring the performance and functionality of the structure (Nojavan et al., 2005).

In the concrete structures, it has been facing a several types of damage mechanism and deterioration during the life time due to factors such as fatigue loading, frost damage, creep, the high loading of structure due to the increasing traffic flow on the bridge and severe environmental effects such as, scaling, spalling and corrosion. Therefore, the process of damaged mechanism in concrete structure will induce the interaction of duration between long term services into short term services (Nair et al., 2009). However, these interaction times of the process also affect the structural conditions and structural integrity.

The facts mentioned proved the importance of early damage detection and timely planning of appropriate maintenance for structural safety performance. Visual inspections by trained inspectors have been used in traditional monitoring. Due to the limitation of visual inspection which cannot detect all damages especially during the early stage, better or more efficient techniques are often required for better result in evaluation system (Kaphle et al., 2011).

One of the most excellent tools in SHM for real time monitoring system is Acoustic Emission (AE). This technique is an effective tool for evaluation of any system without destroying the material conditions enables early crack detections and it has very high sensitivity to crack growth. It is based on the phenomenon whereby high frequency waves are generated from rapid release of energy inside a material such as from initiating and growing cracks (Ohtsu, 1996; Proverbio, 2011). Therefore, this research aims to focus on AE technique for evaluation of the damage mechanism on concrete structure.

## 1.2 Problem Statement

Reinforced concrete (RC) structures have been used in construction since ancient time in major and minor infrastructure, such as bridges, dams, and buildings. However, RC structures face deterioration due to several problems such as ageing, disastrous damage due to earthquakes and environmental effects. In Global, some of the concrete structure such as bridges and buildings in rural area were built over 30 years ago and now considered deficient by current conditions. These factors affect the condition and performance of RC structures. Consequently, assessment of damage deterioration in concrete structure is in great demand and it is vital to maintain the structure both for safety and economic consideration. In any assessment and monitoring system, it is pertinent to utilize a non-destructive (NDT) technique which is robust, reliable and provides real time information on the condition of the structure. The application of AE technique in concrete structures has been utilized for more than a half century and it has been employed for early damage detection and characterization in concrete structures. This application is commonly used and established as a monitoring system in the developed country such as Japan, United State, United Kingdom and China.

In monitoring system, structural concrete bridges are highly risk on the structural condition due to over loading compared to other structures. This condition occurs due to the increase of traffic loading at the daily used on the bridges. The most common defects found on superstructure concrete bridges are micro-cracking and macro-cracking. These types of damage are becoming serious and it has created great concern among the public.

In Malaysia, the most significant issue that have been discussed was the Middle Ring Road 2 (MRR2) flyover bridge at Batu Caves, Selangor whereby 31 defective pillars out of 33 pillars were found on the flyover bridge. According to Malaysia Today (2008), the severe cracking has occurred in many cross beams and many cracks width are greater than the design crack width of 0.25mm. Another case was at the Lebuh Raya Damansara Puchong (LDP), Selangor whereby the soffits of the bridge are showing major crack lines across the highway. Although visual inspection and crack width monitoring were conducted in both cases, these preventive techniques have limitation on the detail in assessment and monitoring.

Hence, the AE technique evaluation method is more effective and accurate for developing the damage grading systems. This system is very useful and significant for assessment on concrete structure such as bridges for daily use and deterioration in building to classify the differences of class condition in concrete structures (Holford et al., 2008).

In AE evaluation method, many researchers have developed the technique to identify the damage mechanism by means of AE signal parameters such as signal strength, hits, amplitude and wave energy (Grosse et al., 2008; Kocur et al., 2010). These AE parameters have been used extensively in evaluation system.

The previous researches have been exploring detail on the cumulative AE hits data parameter analysis method for determining the damage classification in normal concrete (Othsu et al., 2002). In addition, the next group research form Lovejoy et al., 2006 was improved the existing method with analysing the cumulative AE hit based on the percentage of loading set in evaluation of reinforced concrete structure.

According to Liu et al., 2009, by utilizing the AE hits data in parameter analysis method was not promising in determining the damage classification level in reinforced concrete structure. Therefore the cumulative signal strength parameter was used extensively to indicate the precise results in damage evaluation system.

In intensity analysis method, mostly the previous researches have been discusses detailed on signal strength parameter in damage assessment method. Nair et al., 2010 and Proverbio, 2011 were explored particularly this parameter in intensity signal analysis method for evaluation of RC beam to determine the damage level. Degala et al., 2009 was also utilized this parameter to define the level of damage in FRP and normal concrete.

Nevertheless, other AE data parameter such as absolute energy has not been explores particularly in damage classification on RC structure and normally this AE absolute energy parameter was utilize to determine the early cracking on concrete structures. According to that matter, this investigation is focus and emphasize on AE absolute energy parameter in determining the damage classification and grading system in RC structure.

## 1.3 Objectives of Study

The purpose of this research is to further understand of the AE technique and evaluation system, in order to provide a commercial tool for the SHM technique and grading system for assessing the reinforced concrete structure. The three main objectives of this research are:

1. To determine the grading system of damage mechanism levels by means of AE data parameter (Absolute Energy) and Cyclic Load Test (CLT) with existing method analysis.
2. To identify and discriminate the AE data parameters with crack classification (Tensile and Shear movement) due to the Cyclic Load Test System (CLT).
3. To validate the standard grading system with AE data parameter (Absolute Energy) for the evaluation of reinforced concrete structure.

By treating these entire objectives together, it is believed that this study has effectively solved the problems in damage assessment in concrete structure in term of grading system and thereby increasing its applicability as one of the SHM tools.

## 1.4 Scopes of Study

The scopes of this research consist of three major parts:

The initial part is about the laboratory work consists of the beams testing with four point bending test using the hydraulic jack and loading frame. The beams will be tested by cyclic load test system together with the AE monitoring system. Throughout this testing, AE data will be recorded and the observation of the cracks pattern will be made to compare the correlation between actual damage and AE data.

Then, the results from AE signal recorded will be analysed through post-test analysis using the qualitative and quantitative methods. The methods of analysis are Parameter Analysis (PA), b-value, RA-value, Intensity signal analysis (ISA) and Intensity absolute energy analysis (IEA). All these methods are applicable and suitable for analysing the challenging AE data parameters in determining and identifying the damaged grading system in concrete structure.

Eventually, the validity and accuracy of the AE signal analysis will be evaluated by using the detail analysis and the grading system will be developed for the evaluation of the damage in concrete structures. Detailed discussion on different analysis will be presented in the following sections and chapters

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## GLOSSARY OF TERMS FOR ACOUSTIC EMISSION TESTING

**Absolute Energy:** This is a true energy measure of an AE hit which units are measured in attoJoule (aJ). Absolute energy is derived from the integral part of the squared voltage signal divided by the reference resistance over the duration of the AE waveform packet.

**Acoustic Emission (AE):** Elastic waves generated by the rapid release of energy from source within a material.

**AE Count:** The number of times the signal amplitude exceeds the pre-set reference threshold.

**Attenuation:** Loss of amplitude with distance as the wave travels through the test structures.

**Array:** A group of sensors used for source location.

**Broad Band sensors:** High sensitivity over a wide frequency range.

**Burst Emission:** A qualitative term applied to AE when bursts are observed.

**Channel:** A single sensor and related instrumentation for transmitting, conditioning, detecting and measuring a signal.

**Continuous Emission:** A qualitative term applied to AE when bursts or pulse are not discernible.

**Couplant:** A substance providing an acoustic link between the propagation medium and sensor.

**Duration:** The interval between the first and last time the threshold is exceeded by the signal.

**Energy (MARSE):** MARSE (**M**easured **A**rea under the **R**ectified **S**ignal **E**nvelope) energy is relative value proportional to the true energy of the source event.

**Event:** A single AE source produces a transient mechanical wave that propagates in all directions in a medium. The AE wave is detected in the form of hits on one or more channels. Therefore, an event is the group of AE hits received from a single source.

**Felicity Ratio:** The measurement of the felicity effect. It is defined as the ratio between the applied load at which the AE appears during the next application of loading and the previous maximum applied load.

**Global Monitoring:** Large scale monitoring of a structure when no specific flaws are known.

**Hit:** A hit is the term used to indicate that a given AE channel has detected and processed an AE transient.

**H-N Source:** Also known as Hsu-Neilson or lead break; the industry standard calibration method, which involves fracturing a 0.5 diameter, 3mm long, 2h propelling pencil lead at 30° orientation.

**Kaiser Effect:** The absence of detectable AE until the previous maximum applied stress level is exceeded.

**Location Group:** An array of AE sensors (based on known placement between one another) for the purpose of determining the general or exact location of an event occurring near or within the detection area.

**Local Monitoring:** A source location examination of a known flaw.

**Location Plot:** Representation of sources of AE computed using an array of sensors.

**Lockout Time:** The minimum time following the detection of an event before the analysis software resumes event processing within a location group. This is typically set to the period of time taken for an AE signal to propagate from one sensor in a group to the most distant sensor in the given group. Use of lockout time is intended to prevent reflections from a single source event being incorrectly identified as new events by the source location algorithm.

**Noise:** The signal obtained in the absence of any AE, the signal has electrical and mechanical background.

**Parametric Inputs:** Environmental variables (e.g. load, pressure, temperature) that can be measured and stored as part of the signal description.

**Peak Amplitude:** Maximum signal amplitude within the duration of the signal.

**Pencil Lead Fracture:** An artificial source using the fracture of a brittle graphite lead in a suitable fitting to simulate an AE event (also known as an Hsu-Neilson source).

**Rayleigh Wave:** Rayleigh waves are longitudinal and transverse waves which propagate in the bulk of the material combine in the region close to the surface.

**Reference Threshold:** A pre-set voltage level that has to be exceeded before an AE signal is detected and processed.

**Resonant Sensor:** A sensor that uses the mechanical amplification due to a resonant frequency to give high sensitivity in a narrow band.

**Rise-time:** The interval between the first threshold crossing and the maximum amplitude of the signal.

**Sensor:** A device that converts the physical parameters of a wave into an electrical signal.

**Signal Features:** Measurable characteristic of AE signal, such as amplitude, AE energy, duration, counts, rise-time, that can be stored as a part of AE hit description.

**Signal Strength:** The integrals of the rectified voltage signal over the duration of the AE waveform packet.

**Source:** The place where an event takes place.

**Source Location:** The computed origin of AE signal.

**Velocity:** The speed at which an AE wave propagates from one sensor to another